Resolved CO(1 → 0) Nuclei in IRAS 14348-1447: Evidence for Massive Bulge Progenitors to Ultraluminous Infrared Galaxies

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ABSTRACT

High-resolution, CO(1→0) interferometry of the ultraluminous infrared galaxy IRAS 14348-1447 is presented. The merger system has a molecular gas mass of $\sim 3 \times 10^{10}$ M$_\odot$ and a projected nuclear separation of 4.8 kpc (3.5″), making it one of the most molecular gas-rich galaxies known and an ideal candidate for studying the intermediate stages of an ultraluminous merger event. The CO morphology shows two molecular gas components associated with the stellar nuclei of the progenitors, consistent with the idea that the molecular disks are gravitationally bound by the dense bulges of the progenitor galaxies as the interaction proceeds. In contrast, less luminous infrared galaxies observed to date with projected nuclear separations of $\lesssim 5$ kpc show a dominant CO component between the stellar nuclei. This discrepancy may be an indication that the progenitors of mergers with lower infrared luminosity do not possess massive bulges, and that the gas is stripped during the initial encounter of their progenitors. A comparison of the CO and radio luminosities of the NE and SW component show them to have comparable radio and CO flux ratios of $f(NE)/f(SW) \sim 0.6$, possibly indicating that the amount of star-forming molecular gas in the progenitors is correlated with the supernovae rate. The estimate of molecular gas masses of the nuclei and the extent of the radio emission are used to infer that the nuclei of IR 14348-1447 have gas densities comparable to the cores of elliptical galaxies.

Subject headings: galaxies: ISM—infrared: galaxies—ISM: molecules—radio lines: galaxies—galaxies: active—individual: IRAS 14348-1447

1. Introduction

Galaxy tidal interactions and mergers are responsible for the most luminous galaxy phenomenon in the universe, be they starbursts or active galactic nuclei (AGN). The energy sources are fueled by molecular gas, which is subject to gravitational torques, dynamical friction and dissipation during the interaction. As a result, the distribution of young stars in the merger and the efficiency at which an AGN can be built or fueled depends not only on the amount of fuel available, but also on the Hubble-types of the progenitors (e.g., Mihos & Hernquist 1996; Mihos 1999).

The most energetic examples of mergers known are the ultraluminous infrared galaxies (ULIGs: $L_{IR}[8 - 1000\mu m] \gtrsim 10^{12}$ L$_\odot$). ULIGs have been of particular interest in the last 15 years, both because of their extreme starburst environment (e.g. Joseph & Wright 1985) and because of their possible evolutionary connection with QSOs and radio galaxies (Sanders et al. 1988a,b; Mirabel, Sanders, & Kazes 1989).

In order to determine the properties of the progenitors of ULIGs and the mechanisms at work as the progenitors come under the gravitational influence of each other, a program has been initiated to map the distribution of CO(1 → 0) in several ULIGs for which the nuclei of the progenitors have yet to coalesce. In this *Letter*, high-resolution CO(1 → 0) observations of the ULIG IRAS 14348-1447, obtained with the Owens Valley Millimeter Array (OVRO), are presented. With an infrared luminosity $L_{IR} = 1.8 \times 10^{12}$ L$_\odot$ and a molecular gas mass of $\sim 4.2 \times 10^{10}$ M$_\odot$ (Sanders, Scoville, & Soifer 1991), IRAS 14348-1447 is one of the most luminous and molecular gas rich ULIGs that show no definitive evidence of AGN activity (i.e, broad line emission or strong high ionization lines; see Veilleux, Sanders, & Kim 1997). The nuclei have a projected separation of $\sim 3.5''$ (4.8 kpc: Carico et al. 1990; Surace, Sanders & Evans 1999; Scoville et al. 1999), making it ideally suited for the resolution of OVRO. The data presented here show evidence contrary to observations

which have led to suggestions that molecular gas in luminous mergers as a class is stripped and collects between the merging stellar nuclei, but supports recent models that show the molecular disks in massive bulge galaxy-galaxy mergers are gravitationally stabilized against stripping (Mihos & Hernquist 1996; Mihos 1999). An $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ is assumed throughout such that $1''$ subtends ~ 1.4 kpc at the redshift of the galaxy ($z = 0.0825$).

1.1. Interferometric Observations

Aperture synthesis CO($1 \rightarrow 0$) maps of IRAS 14348-1447 were made with the Owens Valley Radio Observatory (OVRO) Millimeter Array during two observing periods from 1999 February to 1999 April. The array consists of six 10.4 m telescopes, and the longest observed baseline was 242 m. Each telescope was configured with 120×4 MHz digital correlators. During the observations, the nearby quasar [HB89] 1334-127 (5.89 Jy at 107 GHz; B1950.0 coordinates 13:34:59.81 -12:42:09.9) was observed every 25 minutes to monitor phase and gain variations, and 3C 273 and 3C 345 were observed to determine the passband structure. Finally, flux calibration observations of Neptune were obtained.

The OVRO data were reduced and calibrated using the standard Owens Valley data reduction package MMA (Scoville et al. 1992). The data were then exported to the mapping program DIFMAP (Shepherd, Pearson, & Taylor 1995), and the NRAO software package AIPs was used to extract spectra.

2. Results

Figure 1a shows a 0.8 μm archival image of IRAS 14348-1447 taken with the Hubble Space Telescope (HST) WFPC2 instrument. The merger consists of two nearly face-on

colliding spirals with a projected nuclear separation of 3.4″ (4.8 kpc). A prominent tidal tail is visible extending northward from the northeastern galaxy (hereafter IRAS 14348-1447NE), and a much fainter countertail extends southward from the southwestern galaxy (hereafter IRAS 14348-1447SW). Knots, or super star clusters, are visible around both nuclei, as well as along the tidal tail of IRAS 14348-1447NE.

Figure 1b shows the CO(1→0) emission of IRAS 14348-1447 in contours superposed on a three-color HST NICMOS (Near-Infrared Camera and MultiObject Spectrometer) image of the ULIG. The CO emission consists of two unresolved components (FWHM = 2.8″ × 1.9″ = 3.9 kpc × 2.7 kpc) which are centered on the respective stellar nuclei of the progenitors. The upper limit of the CO extent in each galaxy is significantly less than the average effective diameter[4] of 11.5±7.5 kpc determined from a sample of $\sim$ 140 nearby spiral galaxies (Young et al. 1995). The total CO flux density of IRAS 14348-1447 is 40.8 Jy km s^{-1} and the CO luminosity is $L'_{CO} = 8.0 \times 10^9$ L$_{\odot}$, with $\sim$ 42% and 68% of the emission emanating from the NE and SW components, respectively. The total CO flux density is 20% less than the flux density derived from the single-dish measurement of IRAS 14348-1447 with the NRAO 12m Telescope (half power beam width, HPBW = 55″: Sanders, Scoville, & Soifer 1991). Such a discrepancy is likely due to flux calibration uncertainties associated with the individual observations, which can each be as large as 15%. Assuming a standard ratio (α) of CO luminosity to H$_2$ mass of 4 M$_{\odot}$ (K km^{-1} s^{-1} pc^{-1})$^{-1}$, which is similar to the value determined for the bulk of the molecular gas in the Milky Way, the total molecular gas mass of the pair is calculated to be 3.2×10^{10} [$\alpha/4$] M$_{\odot}$, or 14 times the molecular gas mass of the Milky Way.[5]

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[4]Young et al. (1995) define the effective diameter to be the diameter that encloses 70% of the total CO emission.

[5]Radford, Solomon, & Downes (1991) have used theoretical models to determine that

Figure 1b also shows the CO(1→0) emission-line spectra extracted from both progenitors. The line profile of IRAS 14348-1447NE appears asymmetric and blueshifted, consistent with the Hα line profile determined from Fabry-Perot observations (Mihos & Bothun 1998), and has a full width at half the maximum intensity line width of $\Delta v_{FWHM} \sim 350$ km s^{-1}. IRAS 14348-1447SW has a more symmetric CO line profile with a $\Delta v_{FWHM} \sim 300$ km s^{-1}. The relative velocity offset of the CO line centroids is approximately 120 km s^{-1}, consistent with the offsets measured from the optical emission lines (Veilleux et al. 1995; Mihos & Bothun 1998). Table 1 summarizes the properties discussed above.

3. Discussion

Figure 1 clearly shows that IRAS 14348-1447 consists of two gas-rich spiral galaxies that have undergone gravitational response to at least one initial close approach. It is also clear that the molecular gas is associated with the individual progenitor nuclei at this stage of the merger process. Further, the LINER (Low Ionization Nuclear Emission-line Regions) emission-line spectra in both nuclei (Veilleux et al. 1995) indicates that shocks from either

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α ranges from 2–5 M$_{\odot}$ (K km^{-1} s^{-1} pc^{-1})$^{-1}$ for a reasonable range of temperatures and densities. Downes & Solomon (1998) have modeled interferometric CO data of a sample of infrared luminous galaxies to derive an $\alpha = 0.8$. Thus, the molecular gas mass of IRAS 14348-1447 may be a low as 6.4×10^9 M$_{\odot}$. However, note that the dynamical mass derived using $\Delta v_{FWHM} = 350$ and 300 km s^{-1}, $r = 108$ and 84 pc (see §3), and assuming the reasonable inclination angle of the disk axis relative to the line-of-sight of 29° and 18° for the IRAS 14348-1447NE and 14348-1447SW disks, respectively, yields masses consistent with the molecular gas mass calculated with $\alpha = 4$ M$_{\odot}$ (K km^{-1} s^{-1} pc^{-1})$^{-1}$.

a low ionization AGN or supernovae resulting from massive starbursts with a total energy output of 1.8×10^{12} $L_\odot$ have commenced. All of these properties can be understood in terms of a merger in which the molecular disks associated with each progenitor have been stabilized against stripping by a dense, massive stellar bulge. Given the upper limit on the gas distribution of IRAS 14348-1447 relative to local spiral galaxies, the interaction has likely already driven the molecular gas inwards, resulting in enhanced nuclear activity (see simulations by Mihos & Hernquist 1996 and Mihos 1999).

Disk stabilization against stripping is also applicable to other intermediate stage ULIGs. Recent observations of Arp 220 have shown that the major CO concentrations in this merger are on the individual stellar nuclei, which have a projected separation of 0.95″ ($\sim$ 350 pc; Sakamoto et al. 1999). Likewise, PKS 1345+12, a ULIG with very warm, Seyfert-like infrared colors relative to Arp 220 and IRAS 14348-1447, shows the CO emission concentrated only on the active radio nucleus, indicating that gas infall and AGN activity has been triggered by interactions with the companion galaxy (Evans et al. 1999). The companion galaxy has colors consistent with an elliptical galaxy (Surace et al. 1998), which explains its lack of detectable molecular gas.

In contrast, the morphologies of all of the lower luminosity luminous infrared galaxies (LIGs: $L_{\rm IR} = 10^{11.0-11.99}$ $L_\odot$) with small ($\lesssim$ 5 kpc) projected nuclear separations observed to date are markedly different; Arp 244, VV 114, NGC 6240, and NGC 6090 have molecular gas predominantly in one component between the two nuclei (Stanford et al. 1991; Yun et al. 1994; Tacconi et al. 1999; Bryant & Scoville 1999). Tacconi et al. (1999) have speculated that the molecular gas in NGC 6240 has been ram-pressure stripped, and that the nuclei may later sweep up gas as the galaxy evolves into ULIGs such as Arp 220. An alternative explanation may be that the processes affecting the gas in LIGs differ from ULIGs because the progenitors of each luminosity class differ. Specifically, ULIGs may

primarily be examples of equal mass galaxy mergers with dense stellar bulges, thus the gas is driven into the nuclear region of the respective progenitors as the merger advances. In contrast, LIGs may be predominantly collisions of galaxies of different masses and relatively low-density bulges (e.g., note the differences in the near-infrared stellar morphologies of the progenitor galaxies of NGC 6090 and VV 114: Dinshaw et al. 1999; Scoville et al. 1999), thus the gas is stripped from the progenitors with extreme efficiency. As a result, many LIGs may never evolve into ULIGs. A larger survey of double nuclei ULIGs, consisting of those with obvious AGN signatures and those without, is underway to investigate the ubiquity of these results. Such a survey will also benefit from kinematic determinations of the stellar bulge masses of the progenitors.

A comparison of the molecular gas and radio fluxes and morphologies of the progenitors of IRAS 14348-1447 can be used to derive the gas densities of the nuclei. The measured IRAS 14348-1447NE to IRAS 14348-1447SW flux density ratios of CO and the 8.44 GHz and 1.49 GHz radio emission (i.e., Condon et al. 1990; 1991) yield values of $f(NE)/f(SW) \sim$ 0.61, 0.62, and 0.58, respectively. The implication of this result is that the molecular gas mass of each component is related to the source of the radio emission. This can be understood if the nuclear radio emission is due to synchrotron emission from supernovae and if both galaxies have similar initial mass functions. Thus, the CO and radio flux density ratios of the progenitors are similar because the same fraction of massive stars are produced per unit of star-forming molecular gas. Therefore, if the likely assumption is made that the extent of the radio emission of each nucleus (FWHM(NE) $\sim 0.16''$ [220 pc] and FWHM(SW) ~ 0.12 [170 pc]) is similar to the true extent of the molecular gas (i.e., the supernovae fill the same volume as the gas they are formed from), then the northeastern and southwestern nuclei have gas densities of $\sim 2.4 \times 10^3$ [$\alpha/4$] and 7.7×10^3 [$\alpha/4$] M$_\odot$ pc^{-3}, respectively. Given the uncertainty in the value of α, the density and the velocity dispersion of the gas in each nucleus are comparable to the stellar densities and velocity

dispersions of elliptical galaxy cores (Faber et al. 1997), supporting the likely connection between ULIGs and the formation of elliptical galaxy bulges (Kormendy & Sanders 1992).

Molecular gas-rich ULIGs in the local universe such as IRAS 14348-1447 may provide insights to the nature of massive galaxy formation in the universe. Figure 2 shows a plot of $CO(1{\rightarrow}0)$ luminosity of LIGs and ULIGs versus their redshift. On this plot, IR 14348-1447 is shown as an asterix enclosed in a circle. The rise in L'_{CO} at $z < 0.04$ is simply due to the space density of the flux-limited infrared luminous galaxy sample. However, the leveling off of L'_{CO} beyond $z > 0.07$ is a possible indication that, due to self regulating processes, galaxies do not contain molecular gas masses in excess of $\sim 4 \times 10^{10} \, [\alpha/4] \, M_{\odot}$ (Evans et al. 1996; Frayer et al. 1999). The observed flatness of L'_{CO} beyond $z \sim 0.07$ remains constant out to redshifts of 4.7 (Frayer et al. 1998). Thus, in terms of the richness of the interstellar medium, galaxies such as IRAS 14348-1447 appear to be the low redshift counterparts of molecular gas-rich, high-redshift galaxies detected over the last decade (e.g. see Frayer et al. 1999 for a summary). If a substantial fraction of these systems have nuclear gas densities comparable to IRAS 14348-1447, then they as a class are the likely progenitors of massive elliptical galaxies.

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Figure Captions

Figure 1.a) Hubble Space Telescope WFPC2 image of IRAS 14348-1447. b) CO(1 → 0) contours of the merger superimposed on a three-color composite NICMOS image (blue=1.1 μm, green = 1.6 μm, red=2.2 μm). The CO contours are plotted as 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 99% the peak flux of 0.0283 Jy/beam. The CO emission for each progenitor is unresolved, with a beam FWHM of $2.8'' \times 1.9''$ at a position angle of -21.6°. Extracted spectra of the SW and NE progenitors are also shown. For the images, north is up and east is to the left.

Figure 2. The plot of $L'_{\rm CO}$ versus redshift (z) for a flux-limited sample ($f_{60\mu m} > 5.24$ Jy) of infrared luminous galaxies and a sample of ultraluminous infrared galaxies. The data have

been obtained from Sanders, Scoville, & Soifer (1991) and Solomon et al. (1997). The data point representing IRAS 14348-1447 is encircled.

Table 1.   Molecular Gas Properties of IRAS 14348-1447

Component	RA	Dec	z	Δv_{FWHM}	$S_{CO}\Delta v$	$M(H_2)^b$
	(B1950.0)^a			km s^{-1}	Jy km s^{-1}	$\times 10^{10}$ M$_\odot$
14348-1447NE	14:34:53.42	-14:47:23.1	0.0823	350	15.6	1.2
14348-1447SW	14:34:53.30	-14:47:26.1	0.0827	300	25.2	2.0
Total	...	...	...	...	40.8	3.2

^{a}The coordinates are taken from Condon et al. (1991).

^{b}The H_2 masses are derived assuming $\alpha = 4$ (see text).

a) WFPC2

5 kpc

b)

CO(1-0)   z=0.0823
NE

S_ν (Jy/beam)

cz (km/s)

CO(1-0)   z=0.0827
SW

S_ν (Jy/beam)

cz (km/s)

NICMOS

ΔRA ('')

ΔDEC ('')